REPORT DOCUMENTATION PAGE

OMB No. 0704-0188 (3)

Publi... gathe... collec... Davis ...age 1 hour per response, including the time for reviewing instructions, searching existing data sources, ...he collection of information. Send comments regarding this burden estimate or any other aspect of this ... Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson ...anagement and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

3. REPORT TYPE AND DATES COVERED
Reprint, 1 May - 1 November 1992

4. TITLE AND SUBTITLE
Diamond and Refractory Coatings of Gun Barrels for Electrothermal-Chemical Launchers

5. FUNDING NUMBERS
DAAL03-92-G-0051

6. AUTHOR(S)
M. Bourham, J. Gilligan, O. Hankins, J. Hurley, W. Eddy and P. Bogdanoff

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
North Carolina State University
Department of Nuclear Engineering
Raleigh, NC 27695-7909

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 30258.2-RT-AAS

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Material surfaces of gun barrels in electrothermal-chemical launchers are subject to high heat fluxes, which may exceed 100 GW/m^2 over 0.01 - 5 ms pulse duration. Such high heat fluxes result in several deforming processes of barrel material, which reduce the efficiency and lifetime of the launcher. The successful operation requires minimum erosion over a large number of repetitive exposures. Diamond and refractory coated barrel material surfaces have been exposed to high heat fluxes from 2 to 60 GW/m^2 over 100 μs duration using the electrothermal launcher, SIRENS. The high heat fluxes produced by SIRENS plasma are primarily from blackbody spectrum photons. The plasma boundary layer "vapor shield" formed by surface vaporization helps to reduce heat transport to the surface. Coatings have been prepared by different methods (sputtering, molten salt, electroplating, chemical vapor deposition and low pressure plasma spray). Surface erosion is caused primarily by convection and radiation emitted from the plasma. The better performance of coated surfaces is attributed to the better thermal conductivity of the heat sink (substrate). Preliminary tests of diamond coating on silicon substrates were not successful because the wafers were destroyed, especially at higher values of incident heat fluxes. SEM micrographs showed that diamond coating has been removed from the silicon surface due to the thermal shock under high pressure.

14. SUBJECT TERMS
Surface erosion, diamond coatings, refractory coatings, diagnostics, ETC launchers.

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

PRESENTED AT THE 29TH JANNAF COMBUSTION MEETING, NASA LANGLEY RESEARCH CENTER, HAMPTON, VIRGINIA, 19-23 OCTOBER 1992

DIAMOND AND REFRACTORY COATINGS OF GUN BARRELS FOR ELECTROTHERMAL-CHEMICAL LAUNCHERS

M.A. BOURHAM, J.G. GILLIGAN, O.E. HANKINS, J.D. HURLEY, W.H. EDDY and P.D. BOGDANOFF
Department of Nuclear Engineering, North Carolina State University
Raleigh, NC 27695-7909

Work supported by the US Army Strategic Defense Command Contract DASG60-90-C-0028, US Army Watervliet Arsenal Contract DAAA22-91-M-4001, and US Army Research Office Contract DAAL03-92-G-0051.

29TH JANNAF COMBUSTION MEETING
NASA LANGLEY RESEARCH CENTER, HAMPTON, VIRGINIA, 19-23 October 1992

DIAMOND AND REFRACTORY COATINGS OF GUN BARRELS FOR ELECTROTHERMAL-CHEMICAL LAUNCHERS

M.A. Bourham, J.G. Gilligan, O.E. Hankins, J.D. Hurley, W.H. Eddy and P.D. Bogdanoff
Department of Nuclear Engineering, North Carolina State University
Raleigh, NC 27695-7909

Work supported by the US Army Strategic Defense Command Contract DASG60-90-C-0028, US Army Watervliet Arsenal Contract DAAA22-91-M-4001, and US Army Research Office Contract DAAL03-92-G-0051.

29th JANNAF Combustion Meeting, NASA Langley Research Center, Hampton, Virginia, 19-23 October 1992

Diamond and Refractory Coatings of Gun Barrels for Electrothermal-Chemical Launchers

M.A. Bourham, J.G. Gilligan, O.E. Hankins, J.D. Hurley, W.H. Eddy and P.D. Bogdanoff*

Department of Nuclear Engineering, North Carolina State University
Raleigh, NC 27695-7909

ABSTRACT

Material surfaces of gun barrels in electrothermal-chemical launchers are subject to high heat fluxes, which may exceed 100 GW/m^2 over 0.01 - 5 ms pulse duration. Such high heat fluxes result in several deforming processes of barrel material, which reduce the efficiency and lifetime of the launcher. The successful operation requires minimum erosion over a large number of repetitive exposures. Diamond and refractory coated barrel material surfaces have been exposed to high heat fluxes from 2 to 60 GW/m^2 over 100 μs duration using the electrothermal launcher, SIRENS. The high heat fluxes produced by SIRENS plasma are primarily from blackbody spectrum photons. The plasma boundary layer "vapor shield" formed by surface vaporization has large temperature and density gradients. The produced vapor due to ablation is injected into that boundary layer and thus the layer thickness increases and its temperature decreases, which results in less heat transported to the surface. The developed pressures in the vapor shield (≥ 1kbar) are large enough to expand against incoming plasma flux, so much of the stored internal energy of the vapor will be propagated away from the surface. Coatings have been prepared by different methods (sputtering, molten salt, electroplating, chemical vapor deposition and low pressure plasma spray). Surface erosion is caused primarily by convection and radiation emitted from the plasma. Mo/Cu has approximately 40% less erosion than pure molybdenum. Ta/Cu showed the lowest erosion, about 88% less than pure molybdenum, while W/Cu and W/Mo have approximately no erosion. Tantalum and tungsten coatings are the most promising among other refractory materials. The better performance of coated surfaces is attributed to the better thermal conductivity of the heat sink (substrate). In case of Mo/Cu the heat sink absorbs ≈ 60% of the heat, while for Ta/Cu, the heat sink absorbs most of the heat (≈ 98%) so that surface erosion is negligible (≈ 0.6 μm at 33 GW/m^2). Preliminary tests of 10-20 μm diamond coating on silicon substrates were not successful because the wafers were destroyed (0.5-3.3 mm thickness silicon wafers are very brittle), especially at higher values of incident heat fluxes. SEM micrographs showed that diamond coating has been removed from the silicon surface due to the thermal shock under high pressure.

Work supported by the US Army Strategic Defense Command Contract DASG60-90-C-0028, US Army Watervliet Arsenal Contract DAAA22-91-M-4001, and US Army Research Office Contract DAAL03-92-G-0051.

*Harvey Mudd College, Claremont, CA 91711, on a National Undergraduate Fellowship in Plasma Physics and Fusion Engineering, Princeton University, sponsored by the US DOE.

INTRODUCTION

The heat fluxes generated during the operation of electrothermal-chemical launchers (ETC) exceed 10 GW/m^2 for a duration of 0.01 - 5 ms, which results in the damage of the launcher components due to erosion. Erosion of the launcher critical components represents a limiting factor that affects the launcher's efficiency, and decreases its lifetime [1-5]. Successful operation of ETC launchers requires minimum erosion of the launcher components. Refractory, or refractory-coated, materials and alloys may help in reducing the erosion of barrels, while ablation of the capillary insulator may be reduced by using high tensile insulating materials [1-2]. Several materials and microcomposites (e.g. CuNb) [6] have been tested to understand their erosion behavior under typical operational conditions experienced in ETC launchers [7-9]. Diamond coatings have been suggested due to the high ablation threshold of diamond surfaces under pulsed high heat loading [10-11]. The plasma boundary layer adjacent to the eroding surface, is characterized by large temperature and density gradients. The vapor produced due to ablation is injected into that boundary layer and thus the layer thickness increases and its temperature decreases, which results in less heat transport to the surface. Such boundary layer (vapor shield) helps to reduce the surface erosion by absorbing a fraction of the incident energy [5,7,10]. The heat flux q" that reaches the surface is represented by $q" = f\,S$, where f is the energy transmission factor through the vapor layer, and S is the incident heat fluence. Absorbed energy appears as vapor shield internal energy which can be transported away from the localized area. Additional surface protection may be achieved via coatings on material surfaces with high thermal conductivity to reduce surface heat flux due to the effectiveness of the heat sink [10].

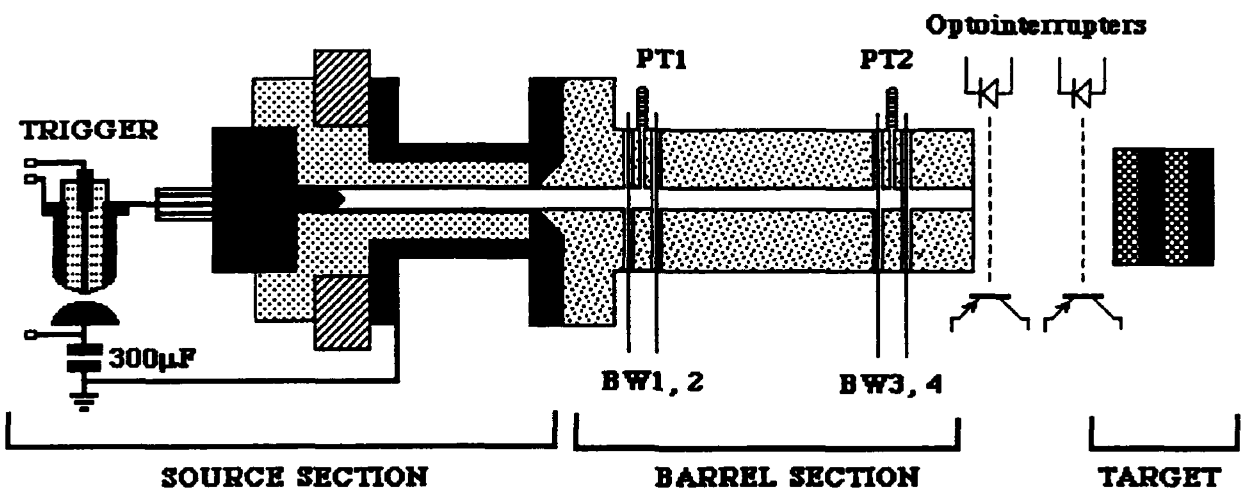
EXPERIMENTAL DEVICE AND DIAGNOSTICS ARRANGEMENT

The experimental device is an electrothermal launcher SIRENS [12,13], which produces high-density (10^{25}-10^{26} $/m^3$) low-temperature (1-3 eV) plasma. The plasma is formed in the source section (capillary) by the ablation of the source insulator (Lexan). SIRENS operates either under vacuum (fuseless operation) or at atmospheric pressure (fuse operation). Table I shows SIRENS operational characteristics (fuseless), while Fig. 1 shows the conceptual design of the launcher with several barrel diagnostics.

TABLE I
SIRENS OPERATIONAL CHARACTERISTICS

Discharge voltage (10 kV max.)	1 - 8 kV
Peak current (100 kA max.)	20-100 kA
Net Input Energy (15 kJ max.)	1 - 8 kJ
Discharge period	100-140 μs
Radiated Power (120 GW/m^2 max.)	2-70 GW/m^2
Peak pressure	> 1 kbar
Plasma density	10^{25}-$10^{26} m^{-3}$
Peak plasma temperature	4 - 6 eV
Average plasma temperature	1 - 3 eV
Average plasma velocity (free expansion)	≈12 km/sec

Material samples are exposed to SIRENS plasma. A fast response thermocouple is attached to the back of the sample to monitor the temperature history. The device has various diagnostics arrangements as shown in Fig. 1. Material diagnostics include the weight loss (microbalance), Scanning Electron Microscopy (SEM), Energy Dissipative X-ray Analysis (EDXA), and Auger Electron Spectroscopy (AES). Signals are digitized via two 8-channel LeCroy waveform digitizers.



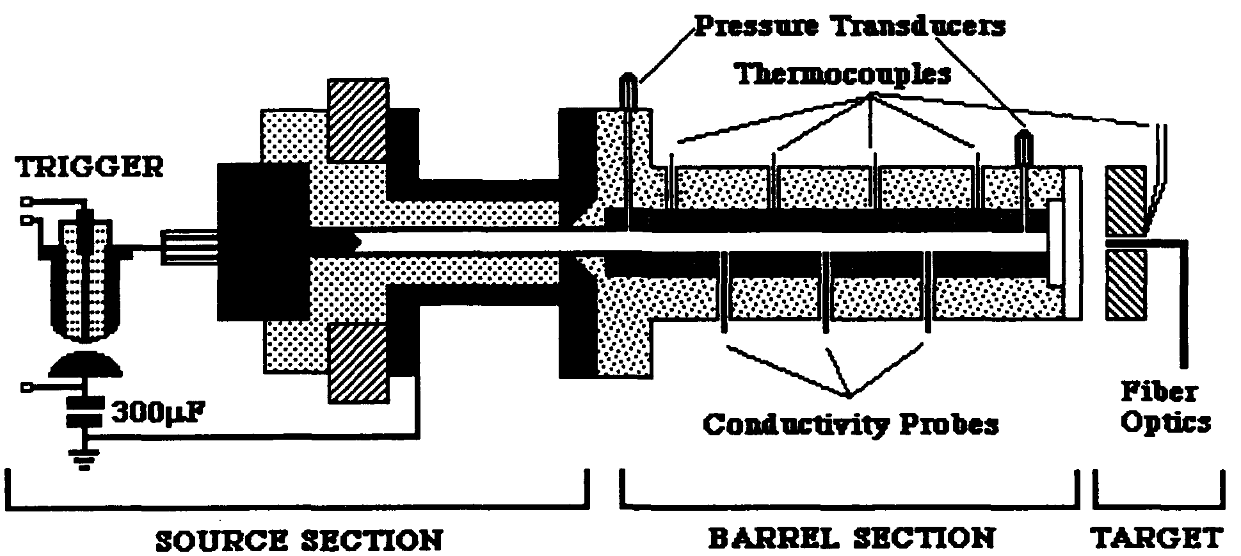


Fig. 1 Schematic drawing of the electrothermal launcher SIRENS showing the plasma source (capillary) and the barrel sections. Several diagnostics can be used. Top arrangement shows pressure transducers (PT1, PT2), break wires (BW1,2,3 and 4), and optointerrupters. Bottom arrangement shows conductivity probes, pressure transducers, and thermocouples.

EXPERIMENTAL RESULTS OF MATERIAL SURFACE EROSION

Several candidate materials coatings and alloys have been proposed as potential components for ETC launchers. Material surfaces were exposed to high heat fluxes up to 70 GW/m^2 over 100 μs (7 MJ/m^2) in SIRENS. Coated surfaces were prepared by Benét laboratory on standard copper substrates (6.35 mm diameter x 3.175 mm thick) using various coating techniques, with 25 to 37 μm coating thickness. Tungsten coatings were prepared by UCLA on molybdenum and copper substrates (25.4 mm diameter x 1 mm thick), with 1mm coating thickness. Diamond coatings were prepared at the NCSU Materials Engineering Laboratories on single crystal silicon wafers (25.4 mm diameter x 0.5 or 3.3 mm thick), with 10-20 μm coating thickness [14]. Samples were exposed to high heat fluxes from 2 to 70 GW/m^2 over 100 μs (0.2 to 7 MJ/m^2 heat fluence). Material samples were ultrasonically cleaned before and after the exposure, and the erosion depths were calculated from weight loss measurements. SEM, EDXA and AES were conducted at NCSU Materials Engineering Analytical Facilities.

The erosion depths Δx of the tested material surfaces have been calculated from the weight loss. Fig. 2 shows a comparison between different coatings on copper exposed to 33 GW/m^2 incident heat flux over 100 μs. Fig. 3 shows the measured erosion depths of several metals tested under the same experimental conditions for purpose of comparison between coated and uncoated surfaces. It is clear, from Fig.2, that the lowest erosion is that of electroplated chromium on copper, sputtered tantalum on copper and sputtered tantalum (with 10% tungsten) on copper coating. LC chromium sputtered on copper has higher erosion, a factor of 15, than electroplated LC Cr. Sputtered HC Cr has also higher erosion than electroplated HC Cr, but only a factor of 5.

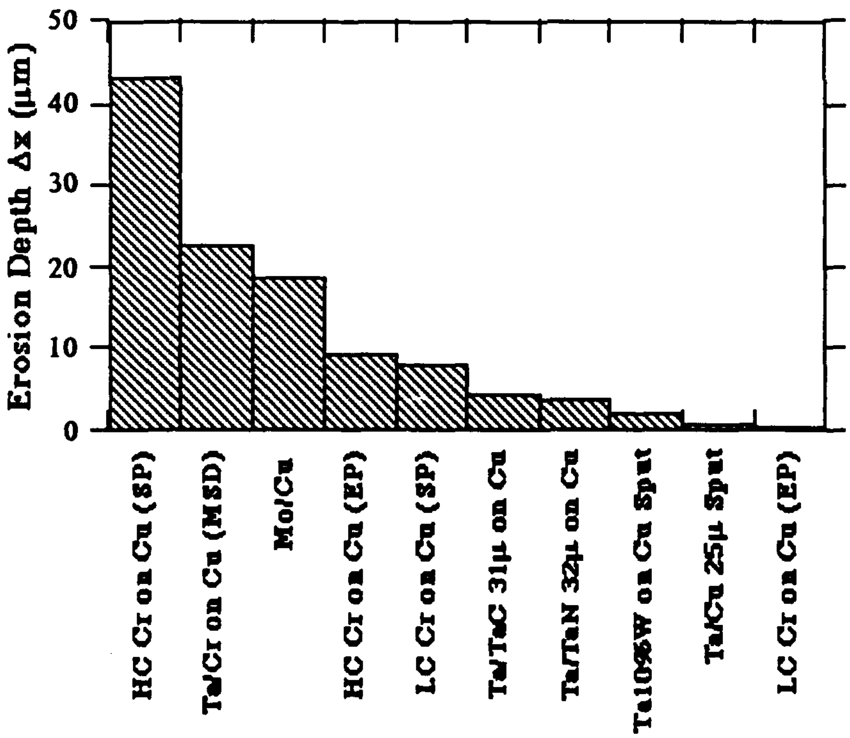


Fig. 2 Erosion depths of coated material surfaces exposed to SIRENS plasma, at 33 GW/m^2 incident heat flux over 100 μs. SP = sputtered, MSD = molten salt deposition, EP = electroplated.

Such comparisou is suggestive that electroplating is better than sputter deposition. This may be attributed to the better contact resistance of electroplated surfaces, which helps for a better heat transfer to the copper bulk to act as an effective heat sink. Fig. 4 shows erosion of three alloys, where tungsten-rhenium metal has approximately no erosion, while HD-17 tungsten alloy has considerably low erosion compared to glidcop (a factor 6 less). A comparison between all the tested samples shows that molten salt deposition (MSD) is not a favorable coating process. Sputter deposition, in general, showed good performance where the contact resistance allows for good heat conduction to the substrate. Electroplating has always good contact resistance and uniform deposition.

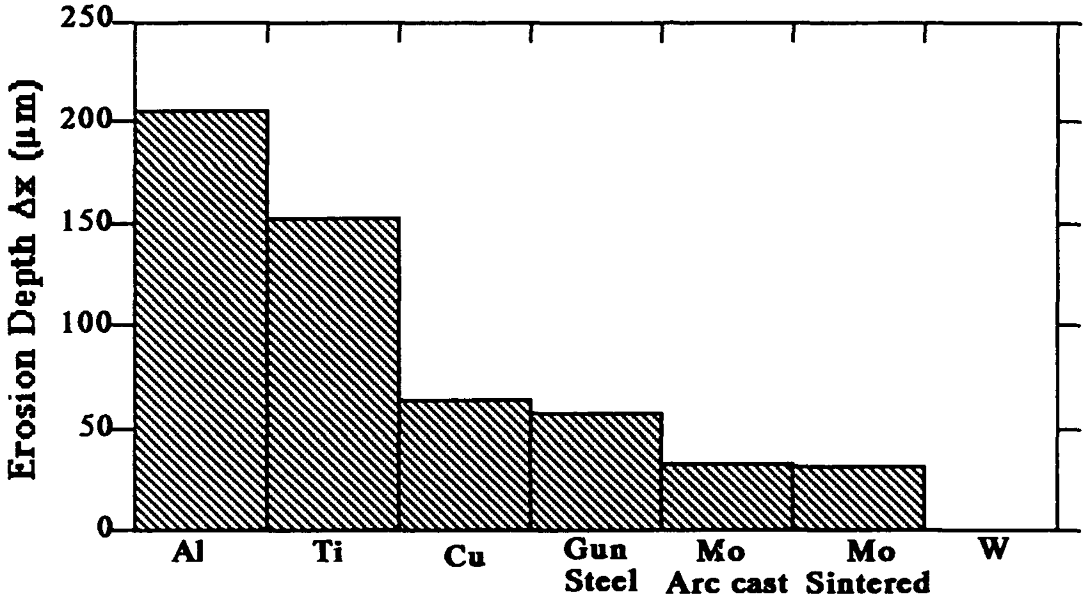


Fig. 3 Erosion depths of pure metal surfaces exposed to SIRENS plasma, at 33 GW/m^2 incident heat flux over 100 μs.

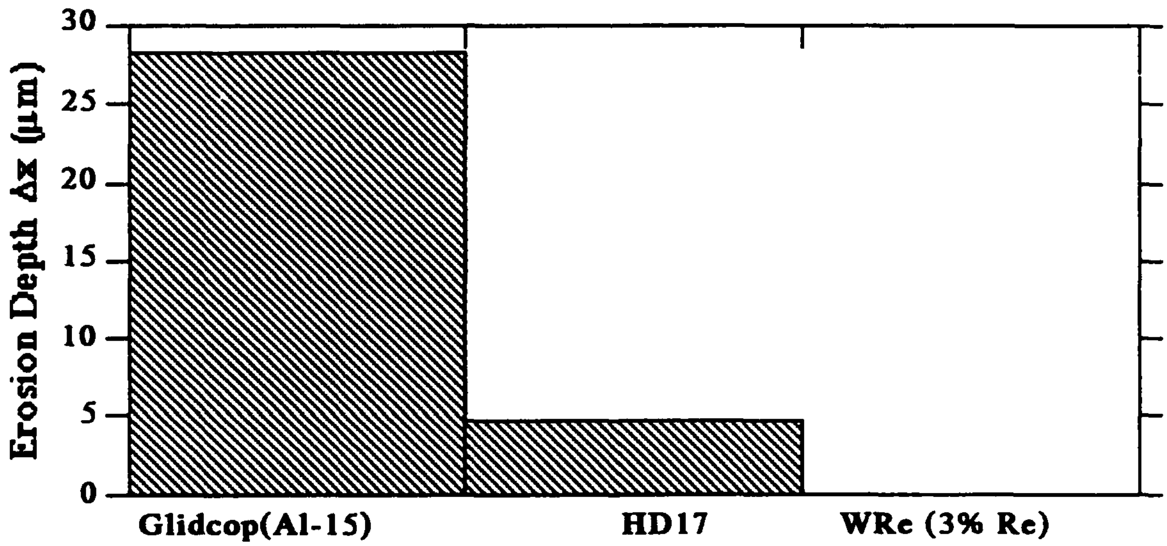
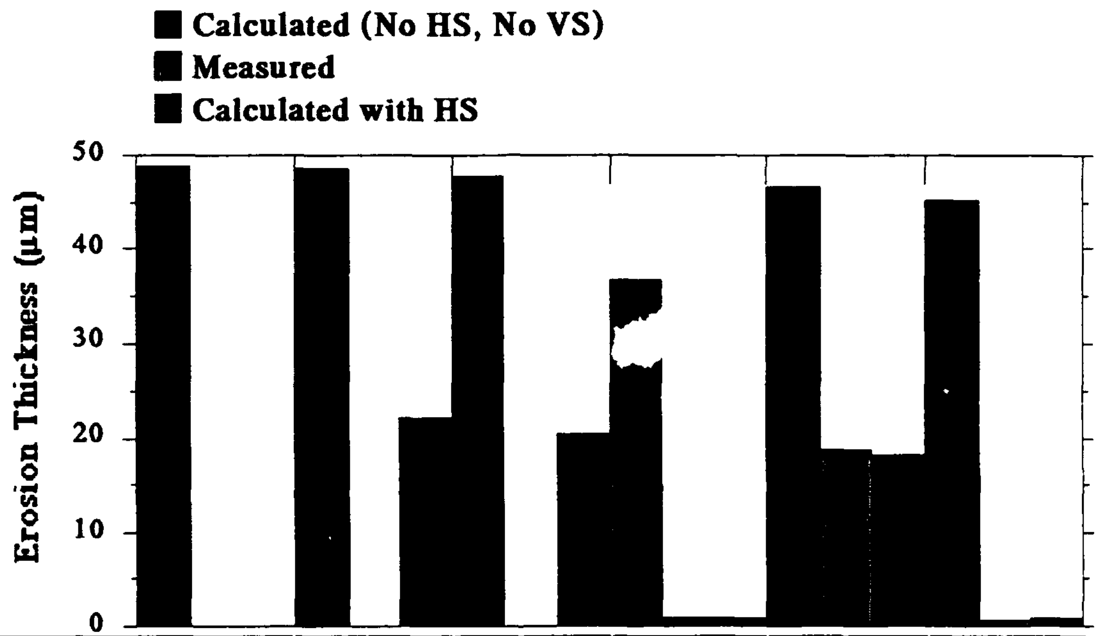


Fig. 4 Erosion depths of several alloys exposed to SIRENS plasma, at 33 GW/m^2 incident heat flux over 100 μs. Glidcop (Al-15) is pure copper alloyed with aluminum oxide (0.15% Al_2O_3), HD17 is a tungsten alloy (90% W, 6% Ni and 4% Cu), WRe is a tungsten rhenium metal (3% Re).

Calculated erosion thickness for chromium, considering full energy deposition, yields 59.5 µm. The experimental results show that erosion thickness is much less for all cases of chromium coating. The experimental erosion values vary from about 1% to 70% of the calculated ones. About 1% for electroplated LC Cr, 16% for electroplated HC Cr, 14% for sputtered LC Cr, and 72% for HC Cr. Surface erosion of electroplated LC Cr is approximately equal to that of sputtered HC Cr. The reduced erosion effect is not only due to the copper heat sink , but also due to the vapor shield effect. Fig. 5 shows a comparison between calculated (with and without heat sink) and measured erosion thickness for tungsten coatings on molybdenum and copper, and molybdenum and tantalum coatings on copper. Calculated erosion with heat sink for coatings on copper substrates correlates well with measured values (W/Cu, Mo/Cu and Ta/Cu).



Material	W (Bulk)	W/Mo (CVD)	W/Mo (LPPS)	W/Cu (Sputter)	Mo/Cu (MSD)	Ta/Cu (Sputter)
Coating thickness		1mm	1mm	37µm	55µm	32µm

Fig. 5 Calculated and measured erosion (33 GW/m^2, 0.1 ms) of pure tungsten, tungsten coating on molybdenum and copper, and molybdenum and tantalum coating on copper. CVD = Chemical Vapor Deposition, LPPS = Low Pressure Plasma Spray, MSD = Molten Salt Deposition. HS and VS stand for Heat Sink and Vapor Shield, respectively.

Ablation studies have been conducted on some insulators commonly used in ETC launchers, at the same incident heat flux of 33 GW/m^2. Fig. 6 shows ablation depths of Lexan, boron nitride, aluminum oxide and glass-bonded mica. Although glass-bonded mica has the lowest ablation depth but melting of the glass-bond may take place at higher heat fluxes. Boron nitride becomes abrasive due to phase transformation from the hexagonal plate structure to the cubic diamond-like structure under the influence of high pressure. Lexan and aluminum oxide have the most uniform ablation under high heat loading and high pressures. The vapor shield effect is very efficient in protecting surface ablation of insulating materials. A comparison between

the energy transmission factor through the boundary layer "vapor shield" is shown in Fig. 7 for Lexan, boron nitride and aluminum oxide. The energy transmission factor through the vapor shield varies between 17 and 25 % for the tested insulators , and decreases to about 5% at incident heat fluxes between 30 and 44 GW/m^2. Fig. 7 shows the variation of the energy transmission factor f with the incident heat flux. The energy transmission factor has been calculated from ablation measurements (experimental data are related to the heat flux reaching the ablating surface) and compared to the source fluence. Although the energy transmission factor for boron nitride is about a factor of 2 less than that of Lexan, the abrasive behavior of boron nitride at higher pressures is undesirable. Aluminum oxide is approximately a factor of 2 less than Lexan at lower values of incident heat fluxes, but they reach the same behavior at higher values.

Erosion studies have been conducted on diamond coatings on single crystal silicon wafers. Two sets of wafers were used, 0.5 mm and 3.3 mm thickness x 25.4 mm diameter. Diamond films were developed by chemical vapor deposition in 2% CH_4 atmosphere at 55 Torr pressure. Film thickness varies between 10 to 20 μm depending upon the total number of scans and processing time (26 to 36 hours). The first two samples were exposed to 33 GW/m^2 incident heat flux (5 kJ input energy to SIRENS capillary at 0.75 kbar capillary pressure). Both samples were destroyed with full removal of the diamond coating from the surface of the silicon wafer. Three samples were exposed at lower heat fluxes (4,2 and 1 GW/m^2), where the source pressure is less than 0.1 kbar. All samples were also destroyed and weight loss could not be obtained. Only surface analysis could be conducted, which revealed that only the sample exposed at 1 GW/m^2 still has some diamond features on the surface. Fig. 8 shows a sample exposed to 33 GW/m^2, and Fig. 9 shows the one exposed to 1 GW/m^2. The top micrograph represents the surface before exposure, while the bottom one is for the same surface after exposure. It is clear from Fig. 8 that diamond coating has been totally removed. The exposed surface of Fig. 9 shows the partial removal and distortion of the diamond film. Stronger material surfaces, other than silicon, are currently under investigation (silicon nitride, tungsten carbide, and possibly Lexan) for potential diamond coating.

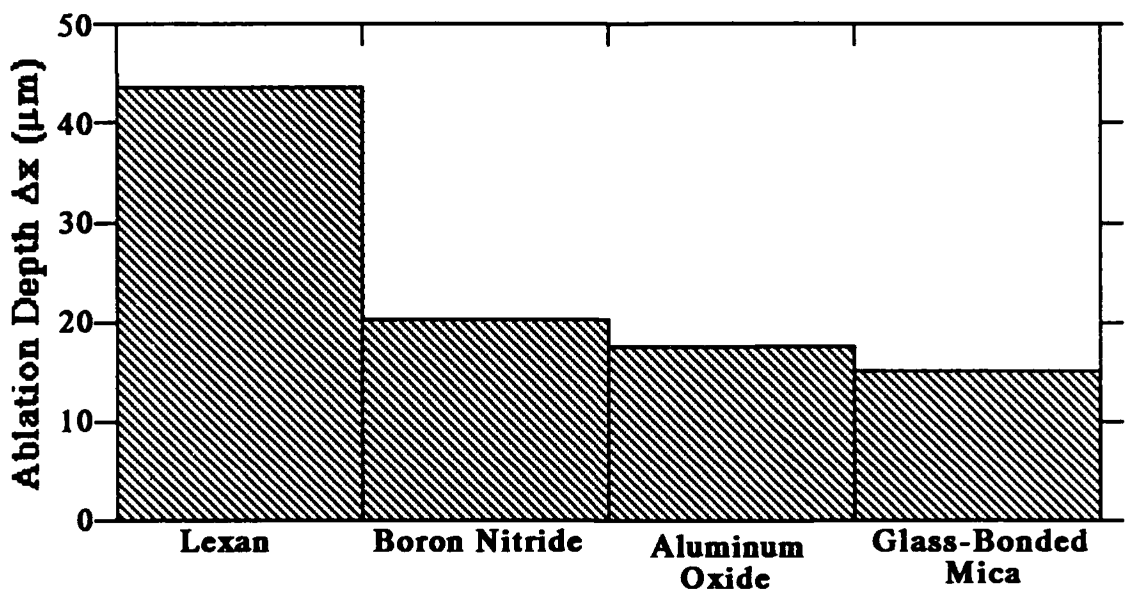


Fig. 6 Ablation depths of insulators commonly used in ETC launchers, exposed to SIRENS plasma at 33 GW/m^2 incident heat flux over 100 μs.

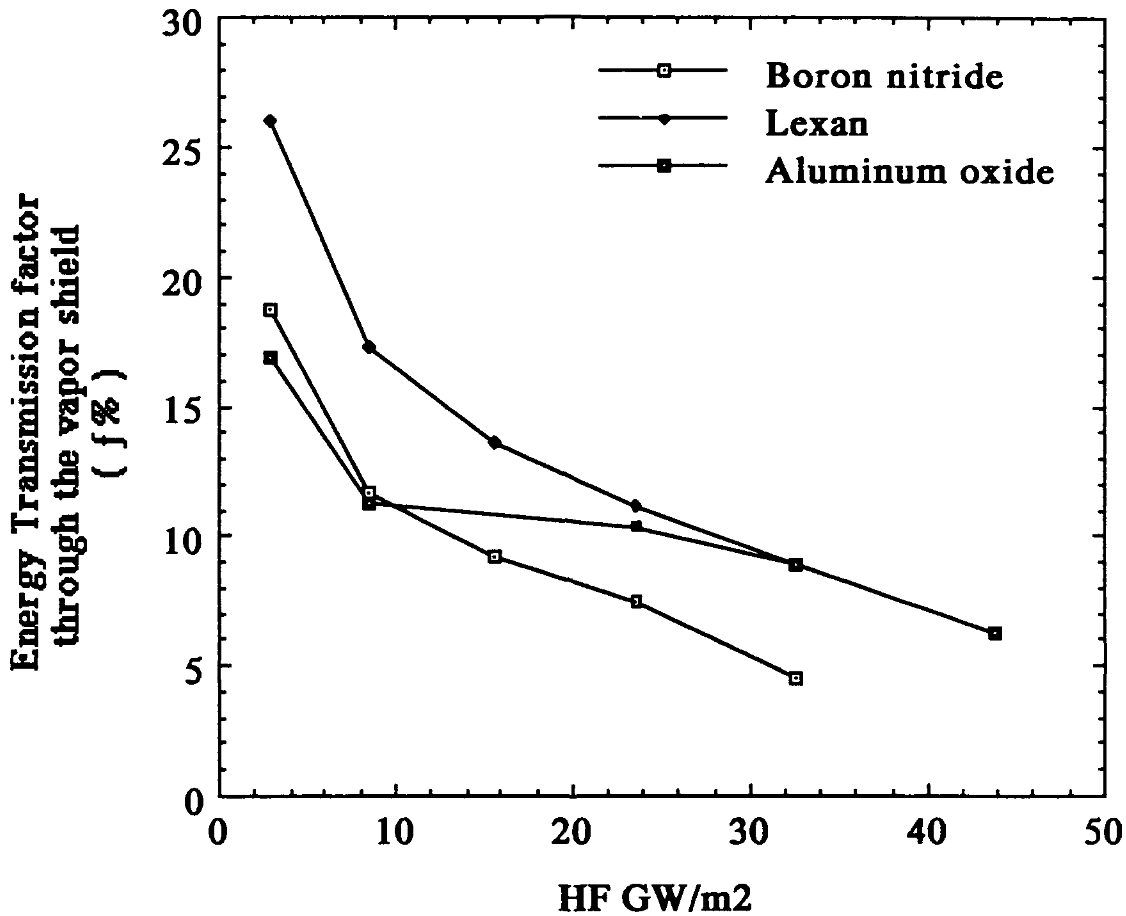
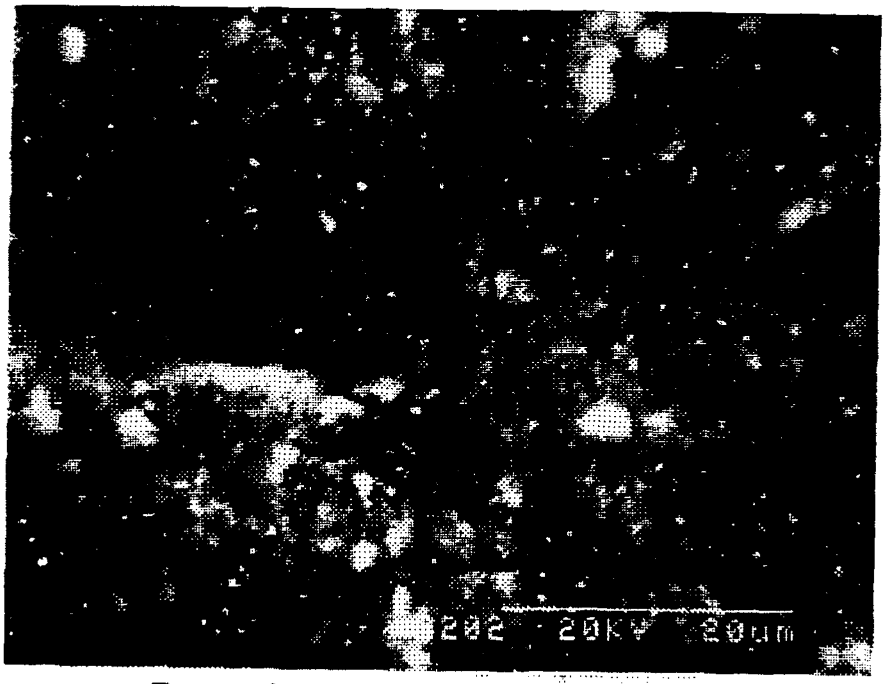


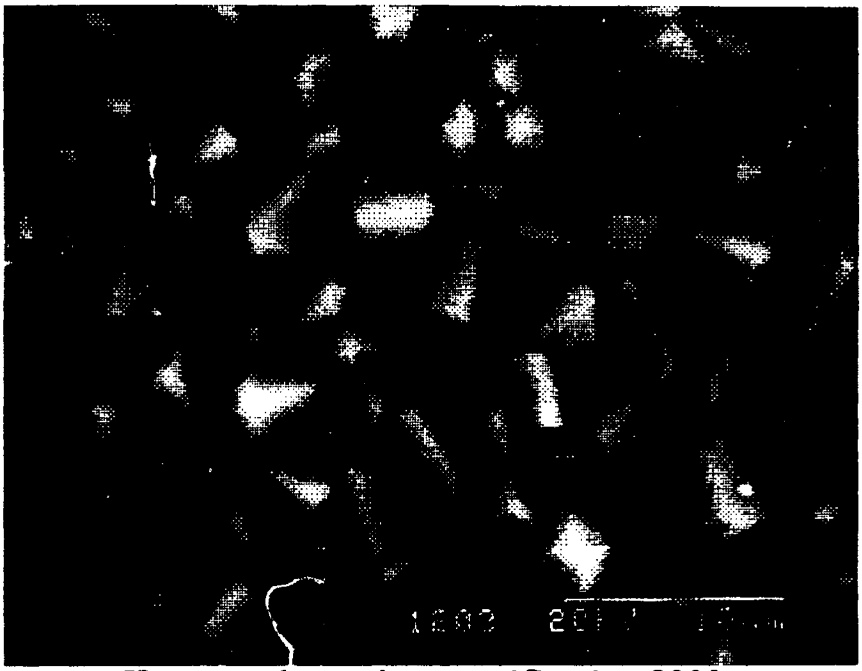
Fig. 7 The energy transmission factor *f* through the vapor shield for the tested insulating materials as a function of the incident heat flux.

Unexposed sample, magnification 5000x



Exposed sample, magnification 2000x

Fig. 8 SEM micrographs of unexposed (top) and exposed (bottom) diamond coating on a single crystal silicon wafer (10-13 μm diamond coating thickness on 25.4 mm diameter x 0.5 mm thick single crystal silicon wafer, coating processing parameters: 2% CH_4, 55 Torr, 300 scans, 26 hours). Shot # 0415, Sample # W26, 33 GW/m^2 incident heat flux.



Unexposed sample, magnification 3000x

Exposed sample, edge of impact, magnification 3000x

Fig. 9 SEM micrographs of unexposed (top) and exposed (bottom) diamond coating on a single crystal silicon wafer (20 μm diamond coating thickness on 25.4 mm diameter x 3.3 mm thick single crystal silicon wafer, coating processing parameters: 2% CH_4, 55 Torr, 420 scans, 36 hours). Shot # 0471, Sample # W-12N, 1 GW/m^2 incident heat flux.

CONCLUSIONS

The erosion of diamond, several candidate coatings and insulator materials have been studied under pulsed high heat fluxes produced in the SIRENS ET launcher for potential applications in ETC launchers. Surfaces were exposed to a standard 33 GW/m^2 heat flux over 100 μs at 0.75 kbar capillary pressure. The lowest erosion noted was for electroplated chromium, sputtered tantalum and sputtered tantalum (with 10% tungsten) coatings on copper. Molten salt deposition showed the worst coating results. Sputter deposition showed good performance where the contact resistance allows for good heat conduction to the substrate. Electroplating has the best contact resistance and uniform deposition. Tested alloys showed that tungsten-rhenium metal has approximately no erosion, while HD-17 tungsten alloy has low erosion compared to glidcop. It has been shown that a good heat sink, with good thermal conductivity, helps to reduce surface erosion. Glass-bonded mica does not withstand higher heat fluxes due to melting of the glass-bond structure. Boron nitride becomes abrasive, most probably due to a phase transformation from the hexagonal plate structure to the cubic diamond-like structure under the influence of high pressure. Lexan and aluminum oxide have the most uniform ablation under high heat loading and high pressures. The vapor shield effect is very efficient in protecting surface ablation of insulating materials. The energy transmission factor through the vapor shield varies between 17 and 25 %, and décreases to about 5% at incident heat fluxes between 30 and 44 GW/m^2. Tests conducted on diamond coating were not successful because the silicon wafers were destroyed (0.5-3.3 mm thickness silicon wafers are very brittle), especially at higher values of incident heat fluxes. SEM micrographs showed that diamond coating had been removed from the silicon surface due to the thermal shock under high pressure. Stronger material surfaces, other than silicon, are currently under investigation (silicon nitride, tungsten carbide, and possibly Lexan) for potential diamond coating.

REFERENCES

[1] F.D. Witherspoon, R.L. Burton and S.A. Goldstein, "Railgun Experiments with Lexan Insulators," IEEE Trans. on Plasma Science, Vol. 17, pp.353-359, June 1989.

[2] J.G. Gilligan, M.A. Bourham and O.E. Hankins, "Ablation and Melting Behavior of Materials in Electrothermal Launchers," 28th JANNAF Combustion Meeting, Brooks Air Force Base, San Antonio, TX, paper I-18, 28 October - 1 November 1991.

[3] J.V. Parker and W.M. Parson, "Experimental Measurement of Ablation Effects in Plasma Armature Railguns," IEEE Trans. on Magnetics, Vol. 22, pp. 1633-1640, November 1986.

[4] A.J. Bedford, "Rail Damage in a Small Caliber Rail-Gun," IEEE Trans. on Magnetics, Vol. 20, pp.348-351, March 1984.

[5] M. Bourham, O. Hankins, O. Auciello, J. Stock, B. Wehring, R. Mohanti and J. Gilligan, "Vapor Shielding and Erosion of Surfaces Exposed to High Heat Load in an Electrothermal Accelerator," IEEE Trans. on Plasma Science, Vol.17, No.3, 386-391 (1989).

[6] A.E. Zielinski and C.V. Renaud, "Erosion Resistance of CuNb Microcomposites in a Plasma Armature Electromagnetic Launcher," U.S. Army Ballistic Research Laboratory, Tech. Rep. BRL-TR-3311, January 1992.

[7] J. Gilligan, M. Bourham, O. Hankins, O. Auciello, S. Tallavarjula and R. Mohanti "Studies to Reduce Material Erosion in Electrothermal Launchers," IEEE Trans. on Magnetics, Vol. 27, No.1, 476-481 (1991).

[8] R.D. Stevenson, S.N. Rosenwasser and R.M. Washburn, "Development of Advanced Ceramic Matrix Composite Insulators for Electromagnetic Railguns," IEEE Trans. on Magnetics, Vol.27, pp. 538-543, January 1991.

[9] J.O. Kolawole, R.V. Frierson, E.J. Clothiaux and C.E. Goodman, "Post-Shot Analysis of Plasma/Rail Interaction in a Small Bore Load Driving EML," IEEE Trans. on Magnetics, Vol.27, pp. 386-391, January 1991.

[10] J. Gilligan, M. Bourham, O. Hankins, W. Eddy, J. Hurley and D. Black, "Vapor Shield Protection of Plasma Facing Components Under Incident High Heat Flux," 10th International Conf. on Plasma Surface Interactions in Controlled Fusion Devices, B:22, Monterey, CA, March 30 - April 3, 1992.

[11] F. Stefani and K. Radford, "Diamond Film Insulators for Railguns," Presented at the 10th Electromagnetic Launcher Association Meeting, Dayton, Ohio, September 15-17, 1992.

[12] O. Auciello, O. Hankins, B. Wehring, M. Bourham and J. Gilligan, "Proof-of-Principle Experiment for the Magnetic Vapor Shield Mechanism," Final Report, DOD Equipment Grant DAAL03-86-G-0157, Nov. 1987.

[13] M. Bourham, J. Gilligan, O. Hankins, W. Eddy and J. Hurley, " Electrothermal Plasma Source as a High Heat Flux Simulator for Plasma-Facing Components and Launch Technology Studies," 9th International Conf. on High-Power Particle Beams, PH-06, 372, Washington, D.C., May 25 - 29, 1992.

[14] J. Glass, Department of Materials Engineering, NCSU, Raleigh, NC 27695, "Private Communication", 1992.